*Attny. Dkt. 0980/62251-C*

# *Application*

# *for*

# *United States Letters Patent*

***To all whom it may concern:***

*Be it known that,*

*Shih-Yuan Wang*

*have invented certain new and useful improvements in*

MICROSTRUCTURED OPTICAL FIBER
TRANSFORMER ELEMENT AND METHOD OF FABRICATION

*of which the following is a full, clear and exact description:*

# MICROSTRUCTURED OPTICAL FIBER TRANSFORMER ELEMENT AND METHOD OF FABRICATION

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## CROSS-REFERENCE TO RELATED APPLICATIONS

Sub A1 This application is a continuation-in-part of U.S. Patent Application Ser. No. 09/591,474, filed June 9, 2000, which is assigned to the assignee of the present invention. This application is related to the subject matter of copending patent applications Ser. No. ___/_______ (Attorney Docket No. G004; 0980/62251-A), Ser. No. ___/_______ (Attorney Docket No. G006; 0980/62251-B), and Ser. No. ___/_______ (Attorney Docket No. G013; 0980/62251-D), each filed on the filing date of the present application and assigned to the assignee of the present invention. Each of the above disclosures is incorporated by reference herein.

## FIELD

This patent specification relates to the field of optical fibers. More particularly, it relates to a transformer element for connecting a microstructured optical fiber to a solid optical fiber and/or to another microstructured optical fiber.

## BACKGROUND

As the world's need for communication capacity continues to increase, the use of optical signals to transfer large amounts of information has become increasingly favored over other schemes such as those using twisted copper wires, coaxial cables, or microwave links. Optical communication systems use optical signals to carry information at high speeds over an optical path such as an optical fiber. Optical fiber communication systems are generally immune to electromagnetic interference effects, unlike the other schemes listed above. Furthermore, the silica glass fibers used in fiber optic communication systems are lightweight, comparatively low cost, and are able to carry tens, hundreds, and even thousands of gigabits per second across substantial distances.

A conventional optical fiber is essentially an optical waveguide having an inner core and an outer cladding, the cladding having a lower index of refraction than the core. Because of the difference in refractive indices, the optical fiber is capable of confining light that is axially introduced into the core and transmitting that light over a substantial distance. Because they are able to guide light due to total internal reflection principles, conventional optical fibers are sometimes referred to as index-guiding fibers. Conventional optical fibers have a solid cross-section and are made of fused silica, with the core region and the cladding region having different levels of dopants (introduced impurities) to result in the different indices of refraction. The cladding is usually doped to have a refractive index that ranges from 0.1% (single mode fibers) to 2% (multi-mode fibers) less than the refractive index of the core, which itself usually has a nominal refractive index of 1.47.

Sub A27 Microstructured optical fibers such as those disclosed in copending Ser. Nos. 09/591,474, ___/_______ (Attorney Docket No. G004; 0980/62251-A), ___/_______ (Attorney Docket No. G006; 0980/62251-B), and ___/_______ (Attorney Docket No. G013; 0980/62251-D) may provide substantially reduced attenuation and dispersion characteristics relative to conventional optical fibers having solid cross-sections. Reduced attenuation and dispersion characteristics allow longer optical fiber spans to carry more information with reduced overall cost and complexity in an optical fiber communications link. A problem, however, arises in the coupling of microstructured optical fibers (hereinafter referred to as MOFs) to solid optical fibers (hereinafter referred to as SOFs) or to other MOFs having different characteristics. In particular, unwanted reflections may occur at the boundary between the MOF and the SOF due to refractive index mismatches. While coupling of MOFs to SOFs is discussed herein, it is to be appreciated that the disclosed methods may be readily applied to the situation of coupling two MOFs having different characteristics. A typical situation in which an MOF would couple to an SOF is in a long-haul optical communications link, in which the long-haul fiber spans are MOF, and in which regularly spaced optical amplifiers comprise erbium-doped fiber amplifiers (EDFAs) having solid cross sections.

Sub A3 ~~FIG. 1 illustrates~~ a diagram of a microstructured optical fiber (MOF) 102 directly coupled to a solid optical fiber (SOF) 104 through a splice ~~or connector 106~~. For

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simplicity and clarity of disclosure, an element that couples two optical fiber ends together is referred to herein as a connector, it being understood that permanent splices and removable connectors may both be used in conjunction with the preferred embodiments described *infra*. As shown in FIG. 1, MOF 102 comprises a core region 108 having a void pattern 116 and a cladding region 110 having a void pattern 118. As described in Ser. No. __/____ (Attorney Docket No. G006; 0980/62251-B), *supra*, the effective indices of refraction $n_{eff1}$ and $n_{eff2}$ of the core region 108 and cladding region 110, respectively, can be represented by Eqs. (1) and (2) below, where $n_1$ and $n_2$ are the core and cladding material refractive indices, respectively, and where $V_1$ and $V_2$ are the core and cladding void-to-cross-section ratios, respectively:

$$n_{eff1} = \sqrt{n_1^2 - (n_1^2 - 1)V_1} \qquad \{1\}$$

$$n_{eff2} = \sqrt{n_2^2 - (n_2^2 - 1)V_2} \qquad \{2\}$$

As an example, where $n_1 = n_2 = 1.470$, $V_1 = 50.0\%$, and $V_2 = 50.2\%$, the effective indices of the core and cladding would be about 1.257 and 1.256, respectively. In contrast, however, SOF 104 comprises a core region 112 and a cladding region 114 having respective indices of refraction that are typically, for example, about 1.470 and 1.485. This refractive index mismatch causes unwanted reflections and loss of signal power as an optical signal traverses the MOF-SOF boundary. Moreover, MOF 102 and SOF 104 may have substantially different core sizes. For single-mode fibers, for example, MOF 102 may have a core diameter of 20 μm, for example, while SOF 102 may have a core diameter of 9 μm. This, in turn, may also result in substantial losses and disturbance of single-mode propagation conditions as the signal traverses the MOF-SOF boundary. Similar core and cladding size variations, and the resulting losses therefrom, may also occur where the MOF 102 and SOF 104 are multimode fibers.

Accordingly, it would be desirable to provide a device for coupling microstructured optical fibers (MOFs) to solid optical fibers (SOFs) that reduces unwanted reflections and other losses that would occur at a direct MOF-SOF boundary.

It would be further desirable to provide a device for coupling two MOFs having different cross-sectional characteristics or refractive index profiles.

It would be still further desirable to provide a method of fabrication of such a device.

## SUMMARY

In accordance with a preferred embodiment, a microstructured optical fiber transformer element is provided for connecting a microstructured optical fiber (MOF) to a solid optical fiber (SOF), the transformer element comprising an MOF-matched first end, an SOF-matched second end, and an adiabatic transition region therebetween. The adiabatic transition region comprises void patterns that gradually change over its length from an MOF-matched void pattern at the first end to a solid cross-section at the second end. The optical material of the transformer element has a refractive index profile designed to cause the adiabatic transition region to have a core size and effective refractive index profile matching those of the MOF at the first end, and matching those of the SOF at the second end, with slow, incremental changes in the core size and effective refractive index profile between the first and second end. Preferably, changes in void sizes, void patterns, core size, and effective refractive index are incremental and occur only over a distance that is many times the wavelength of the light passing through, for example, tens of thousands or hundreds of thousands of wavelengths. In this way, an optical signal entering one end will experience an adiabatic transition in passing through to the other end, in that mode energy is conserved and reflections are minimized or reduced.

In one preferred embodiment, the voids in the cross-section of the transformer element substantially maintain the size and pattern of the MOF-matched first end, except that they gradually dwindle in number as the distance from the MOF-matched first end increases. In another preferred embodiment in which the MOF core is larger than the SOF core, the core voids and center-to-center pattern thereof each shrink in a gradual and proportional manner with increasing distance from the first end, such that the voids disappear and the core size shrinks to the SOF core size at the second end. Each void is thereby individually tapered over the length of the adiabatic transition region. The cladding voids likewise also decrease in size from the first end to the second end, while

their center-to-center pattern stretches radially to fill the increasing cladding cross-section. The material refractive index profile must be selected such that a slow, gradual change in the core size and effective refractive index profile is achieved between the first and second ends.

Many different void profiles and material refractive index profiles are within the scope of the preferred embodiments, provided that these profiles change only gradually with axial distance from being MOF-matched at the first end to being SOF-matched at the second end. A microstructured optical fiber transformer element for connecting two different MOFs is similar to the above MOF-SOF transformer element, except that the ends of its adiabatic transition region are matched to the characteristics of the respective MOFs.

A method for fabricating a microstructured optical fiber transformer element according to a preferred embodiment comprises the steps of creating a preform, drawing the preform into a thin optical fiber, and then clipping away extraneous portions from the ends thereof. The preform is created by generating a plurality of component wafers representing longitudinally consecutive portions of the preform, and then bonding the component wafers together. Sacrificial end portions are then added to each end to enable the drawing process. The sacrificial end portions are clipped away from the resulting fiber after the drawing process, leaving the desired transformer element.

A component wafer may be created by removing a thin slice from a conventionally-made preform and applying a chemical-mechanical polishing process to the slice until the desired thickness is reached. Alternatively, the component wafer may be formed having a desired refractive index profile by a flame hydrolysis process similar to processes used in planar waveguide technology.

In another preferred embodiment, the component wafer is grown by forming a layer of $SiO_2$ using a chemical vapor deposition process or similar semiconductor fabrication process known to grow $SiO_2$. In still another preferred embodiment, the component wafer may be formed by oxidizing silicon (Si) to form a layer of $SiO_2$ thereon, in a process similar to a known semiconductor fabrication processes. The refractive index profile of each component wafer may be initially achieved and/or modified by a hybrid chemical/lithographic process.

In a preferred embodiment, prior to bonding, each component wafer has a void pattern and a material refractive index profile corresponding to its respective longitudinal location in the preform, and thus to its eventual longitudinal location in the transformer element. The desired void pattern is formed into each wafer using a lithographic masking and etching process analogous to like processes used in semiconductor fabrication, and therefore a high degree of pattern complexity and precision may be achieved. In an alternative preferred embodiment, prior to bonding, the component wafers only have the desired material refractive index profiles. The component wafers are bonded into a bonded stack. The desired void pattern is then lithographically formed into the bonded stack prior to attachment of the sacrificial end portions.

The component wafer bonding process is similar to $SiO_2$-$SiO_2$ bonding processes known in the semiconductor fabrication field. Depending on which of the above methods is used to generate the component wafers, each component wafer lies on its own silicon substrate, or if no such substrate is present, one is attached. A first and second component wafer are bonded together, and the silicon substrate now on top of the two-element stack is removed. A third component wafer is bonded to the two-element stack, and the silicon substrate now on top of the three-element stack is removed, and so on. In an alternative embodiment, a massively parallel process is used, such that where $2^N$ component wafers need to be bonded, $2^{N-m}$ groups of longitudinally adjacent stacks of $2^m$ wafers each are bonded together two at a time in separate but concurrent fashion, resulting in $2^{N-m-1}$ groups of longitudinally adjacent stacks of $2^{m+1}$ wafers each, where $m = 0, 1, 2, \ldots N-1$. Thus, by using parallel construction of many adjacent portions of the bonded stack, time is saved as compared to incrementally building a common bonded stack one wafer at a time.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a microstructured optical fiber directly coupled to a solid fiber in which unwanted reflections may occur;

FIG. 2 illustrates a microstructured optical fiber transformer element in accordance with a preferred embodiment;

FIG. 3 illustrates a microstructured optical fiber transformer element in accordance with a preferred embodiment;

FIG. 4 illustrates a material refractive index profile, a void ratio profile, and an effective refractive index profile of an adiabatic transition portion of a microstructured optical fiber transformer element in accordance with a preferred embodiment;

FIG. 5 illustrates a microstructured optical fiber transformer element in accordance with a preferred embodiment;

FIG. 6 illustrates steps for fabricating a microstructured optical fiber transformer element in accordance with a preferred embodiment;

FIGS. 7A and 7B illustrate steps for forming a bonded stack of component wafers in accordance with a preferred embodiment;

FIG. 8 illustrates steps for fabricating a microstructured optical fiber transformer element in accordance with a preferred embodiment; and

FIGS. 9A and 9B illustrate steps for forming voids into a bonded stack of component wafers in accordance with a preferred embodiment.

## DETAILED DESCRIPTION

FIG. 2 illustrates a microstructured optical fiber transformer element 202 in accordance with a preferred embodiment. Transformer element 202 is inserted between the MOF 102 and the SOF 104 of FIG. 1, connecting to them through connectors 204 and 206, respectively. Transformer element 202 comprises an MOF-matched end region 208, an SOF-matched end region 212, and an adiabatic transition region 210 therebetween. In the embodiment of FIG. 2, the MOF 102 and SOF 104 have substantially similar core sizes. MOF-matched region 208 comprises a core 214 and a cladding 222 as shown in cross-section A-A' of FIG. 2. Core 214 comprises a plurality of voids 215, while cladding 222 comprises a plurality of voids 223. The refractive index profile of MOF-matched region 208 is substantially identical to the refractive index profile of MOF 102, and void patterns 215 and 223 are likewise substantially identical to the void patterns in MOF 102. Importantly, MOF-matched end 208 may be very short in length, even down to an infinitesimally small length. However, for reliability of fabrication of the transformer element 202, MOF-matched end 208 should generally have some measurable length.

SOF-matched region 212 comprises a core 220 and a cladding 228 as shown in cross-section D-D' of FIG. 2. Preferably, core 220 and cladding 228 have solid cross-

sections and their refractive index profiles are matched to those of SOF 104. As with the MOF-matched region 208, SOF-matched region 212 may be very short in length, but preferably have some measurable length.

Adiabatic transition region 210 lies between MOF-matched region 208 and SOF-matched region 212 as shown in FIG. 2, meeting them at an MOF-matched end 209 and an SOF-matched end 211. A distance z is used herein to denote a longitudinal distance from MOF-matched end 209 toward SOF-matched end 211, as shown in FIG. 2. Adiabatic transition region has a length $L_A$ sufficiently long such that changes in void sizes, void patterns, core size, and effective refractive index are incremental and occur only over a distance that is many times the wavelength of the light passing through, for example, tens of thousands or hundreds of thousands of wavelengths.

As known in the art, where the changes are gradual enough compared to the wavelength of light passing through, the transition will be essentially adiabatic and reflections will be minimized or reduced. With gradual enough changes, any mode change occurs essentially adiabatically along the optical fiber, minimizing or reducing reflections. Most generally, an adiabatic change refers to a very slow change compared to an equilibrium maintaining process which occurs at a definite rate. In the present context, an adiabatic change refers to a change which is slow compared to the rate of energy redistribution which occurs due to diffraction within the optical fiber and which maintains the light in the mode(s) characteristic to the optical fiber. According to a preferred embodiment, where the wavelength of light passing through is approximately 1 micron, the length $L_A$ would have a minimum length of about 1 cm. In general, common lengths of the adiabatic transition region 210 would lie between 10 cm and several meters in accordance with a preferred embodiment. However, even longer lengths of tens of meters to several kilometers or even more are within the scope of the preferred embodiments.

As shown in cross-sections B-B' and C-C' of FIG. 2, the adiabatic transition region 210 comprises core void patterns and cladding void patterns in which the size of the individual voids remain generally constant, but the number of voids slowly dwindles with increasing distance z. Exemplary core slices 216 and 218 maintain substantially the same core size as that of MOF-matched end 209. However, core slice 218 comprises a void pattern 219 having fewer holes than a void pattern 217 of core slice 216. Similarly,

exemplary cladding slices 224 end 226 maintain substantially the same cladding size as that of MOF-matched end 209. However, cladding slice 226 comprises a void pattern 227 having fewer holes than a void pattern 225 of cladding slice 224. Importantly, the material refractive index of the core and cladding of adiabatic transition element 210 must also slowly vary between MOF-matched end 209 and SOF-matched end 211 such that, given the void patterns at respective slices along the adiabatic transition element 210, the effective refractive indices of the core and cladding make smooth transitions between their MOF-matched values and their SOF-matched values. Computation of the proper material indices for a given void pattern and desired effective refractive index can be accomplished using Eqs. (1) and (2), *supra.*

FIG. 3 illustrates a transformer element 302 in accordance with a preferred embodiment comprising an MOF-matched region 308, an MOF-matched end 309, and SOF-matched end 311, and an SOF-matched region 312 similar to those described *supra* with respect to FIG. 2. However, in the embodiment of FIG. 3, an adiabatic transition region 310 is configured such that its cross-sectional voids slowly taper from one end to the other, while the center-to-center spacings in the void pattern remain substantially the same. As with the embodiment of FIG. 2, it is presumed that the core sizes of the MOF 102 and the SOF 104 are substantially similar. Where B-B' represents a cross-section closer to the MOF-matched end 309 than a cross-section C-C', a core slice 316 and cladding slice 324 at B-B' have void patterns 317 and 325 similar in spacing to void patterns 319 and 327 of a core slice 318 and cladding slice 326 at C-C', but having greater void diameters.

FIG. 4 illustrates a conceptual graph of the void ratio V(z), effective index of refraction $n_{eff}(z)$, and material index of refraction $n_t(z)$ corresponding to the adiabatic transition region 310 of FIG. 3. The plots of FIG. 4 apply to a given x-y point in a cross-sectional slice of the adiabatic transition region 310 as the distance z is increased from 0 to $L_A$. While an x-y point corresponding to the core region is selected for purposes of FIG. 4, the plot of V(z) also applies to any point x-y in the cladding, and the plots $n_{eff}(z)$ and $n_t(z)$ would apply to an x-y point in the cladding assuming an incremental shift corresponding to the index differences between the regions. An exemplary set of parameter values, presented by way of example only and not by way of limitation, includes an MOF having a

core material refractive index of 1.47, a core void ratio of 50%, and a corresponding effective core refractive index $n_{effM}$ of about 1.235. The exemplary set of parameter values further includes an SOF having a core refractive index $n_s$ of 1.485. As shown in FIG. 4, the adiabatic transition region 310 is selected to have a linear change in the void ratio V(z) and the effective index of refraction $n_{eff}(z)$ with the distance z. However, in order to maintain these desired characteristics, the material refractive index $n_t(z)$ must change quadratically with the distance z to satisfy Eq. (1), *supra*.

Importantly, given the present disclosure, a person skilled in the art would readily be able to design a microstructured optical fiber transformer element having an adiabatic transition region with any of a variety of different void profiles and/or material refractive index profiles. A transformer element having any of such various void/refractive index profiles is clearly within the scope of the preferred embodiments, provided only that the void/refractive index profiles change substantially gradually with axial distance. Moreover, given the present disclosure, a person skilled in the art would readily be able to design a microstructured optical fiber transformer element for connecting two different MOFs (e.g., MOF1 and MOF2). Such MOF1-MOF2 transformer elements are also clearly within the scope of the preferred embodiments, provided that the respective ends of the adiabatic transition region are matched to the void and refractive index profile characteristics of MOF1 and MOF2, respectively.

FIG. 5 illustrates a conceptual cutaway view of an adiabatic transition region 502 of a transformer element in accordance with a preferred embodiment, in which the core sizes of the MOF and SOF are different. For clarity of disclosure, only a small number of core voids 508 and cladding voids 510 are shown. The adiabatic transition region 502 comprises a core region 504 and a cladding region 506, the core region 504 slowly tapering in size from a microstructured core diameter $d_{CORE,M}$ at an MOF-matched end 509 to a solid core diameter $d_{CORE,S}$ at an SOF-matched end 511. According to a preferred embodiment, both the individual core void sizes and the center-to-center core void patterns shrink proportionally according to the distance z. To achieve a linear decrease in void to cross-section ratio, linear dimensions such as void diameter would be designed to shrink by a factor of the square root of the distance z normalized by the length $L_A$. As drawn in FIG. 5, which shows a linear shrinking of void diameters with the distance z, the void to

cross-section ratio decreases quadratically with the distance z. Both of these cases, and many other different profiles, are within the scope of the preferred embodiments, provided that slow, incremental changes are made to allow for an adiabatic transition of a signal through the transformer element with minimal reflections.

Because the core region shrinks in size from the MOF-matched end 509 to the SOF-matched end 511, the cladding region 506 necessarily increases in size due to its decreasing inside diameter, *i.e.*, an annulus occupied by the cladding region has an inner diameter that slowly decreases. According to a preferred embodiment, the center-to-center pattern formed by the cladding voids radially stretches toward the axis of the transformer element 502 as the distance z increases. However, the size of the individual voids themselves decreases proportionally according to the distance z, in a manner similar to the core void sizes. In a manner similar to that described with respect to FIG. 4, the material refractive index profile of the cladding region must be adjusted with the distance z in order to maintain the proper effective index of refraction.

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~~FIG. 6 illustrates steps for fabricating a microstructured optical fiber transformer element in accordance with a preferred embodiment. In general, the preferred method uses several steps similar to those described in Ser. No. ____/_____ (Attorney Docket No. G013; 0980/62251-D) that are modified for allowing the void pattern and the refractive index profile to change with axial distance. At step 602, component wafers having desired refractive index profiles are generated. The component wafers generally comprise doped silica glass and may be, for example, anywhere from 1-10 microns thick. According to one preferred embodiment, at least 20 component wafers of incrementally different void patterns and refractive index profiles are used to achieve a sufficiently gradual transition in the adiabatic transition region. However, as more component wafers are used, for example 100 or more, the transition of an optical signal through the adiabatic transition region becomes even closer to a perfect adiabatic transition.~~

The MOF-matched region (see FIG. 2, element 208) and the SOF-matched region (see FIG. 2, element 210) will usually be formed from only a few wafers each, identical to the MOF- or SOF- matched end wafers of the adiabatic transition region to which they are bonded (see FIG. 2, elements 209 and 211). For simplicity and clarity of explanation, the

fabrication of a transformer element with only a single MOF-matched end wafer and only a single SOF-matched end wafer is described.

Because of their material and dimensions, the component wafers are highly amenable to lithographic processes used in semiconductor fabrication. Many such methods are described, for example, in Plummer, *Silicon VLSI Technology: Fundamentals: Practice and Modeling,* Prentice Hall (2000), which is incorporated by reference herein. Although component wafer thicknesses between 1-10 microns are described below, thicknesses below 1 micron (and above 10 microns) would nevertheless be within the scope of the preferred embodiments. There is a general trade-off between increasing the gradualness of the adiabatic transition region, which requires an increased number of component wafers, and increasing the resulting length of the transformer element. For example, where the preform diameter is contracted by a typical factor of 1000 during the drawing process, its cross-sectional area will contract by a factor of 1,000,000, and therefore its length will expand by a factor of 1,000,000. Accordingly, for each component wafer having a thickness of $\Delta t$, there will result a section of transformer element having a length of $1{,}000{,}000\Delta t$. Thus, for example, a 1 micron wafer will result in 1 m of transformer element length; a 100-step transformer element using 100 of these wafers will be 100 meters long. While such dimensions are indeed acceptable for practical applications, it will be more desirable to use sub-micron wafers as the state of VLSI technology, and device fabrication technologies in general, continue to advance. Thus, using 0.1 micron wafers, each wafer will only result in 10 cm of transformer element, and a 100-step transformer element using 100 of these wafers will be 10 meters long. Using 0.01 micron wafers, each wafer will only result in 1 cm of transformer element, and a 100-step transformer element using 100 of these wafers will be only 1 meter long.

At step 604, the desired void patterns are lithographically formed in the component wafers using methods such as those described in Plummer, *supra*. Accordingly, a high degree of pattern complexity and precision may be achieved. Preferably, a dry etch is preferred to a wet etch, as the dry etch is more anisotropic (i.e., more directional) and the void dimensions will be more precise. However, if the component wafers are extremely thin, either dry or wet etching may be used. At step 606, the component wafers are bonded

together into a bonded stack, as will be described further *infra* with respect to FIGS. 7A and 7B.

At step 608, a sacrificial preform is attached to each end of the bonded stack. Both sacrificial preforms have an identical diameter to the bonded stack. Since the bonded stack will generally have a very short length (as small as 20 microns, for example), the sacrificial preforms are attached to enable a conventional optical fiber drawing process to be applied to the bonded stack. At step 610, the resulting preform is drawn using an otherwise conventional optical fiber drawing process. Finally, at step 612, extraneous end portions corresponding to the sacrificial preforms are removed.

The step 602 of generating component wafers with desired refractive index profiles may be carried out using a variety of methods in accordance with preferred embodiments. In one preferred embodiment, a component wafer is created by mechanically removing a thin slice from a conventionally made preform. Accordingly, if N component wafers of successively different refractive index profiles are desired, then N separately-generated preforms will be required. The mechanical process of removing a thin slice can usually only be expected to yield a wafer as thin as about 4 mils (about 100 microns). To achieve the desired thickness, a chemical-mechanical polishing process may be applied until the desired thickness is reached.

In another preferred embodiment, a component wafer is grown by forming a layer of silicon dioxide using a chemical vapor deposition (CVD) process or any semiconductor fabrication process known to grow silicon dioxide. Examples include plasma-enhanced chemical vapor deposition (PECVD), thermal oxidation, ion implantation, sputter deposition, and thermal deposition. One applicable CVD process is described in Wu, B., and Chu, P., "Fabrication of High Concentration Rare-Earth-Doped Silica-Based Waveguide by MCVD Method," IEEE Photonics Technology Letters, Vol. 7, No. 6 (June 1995), pp. 655-657, which is incorporated by reference herein. The refractive index profile of the wafer may be achieved by a hybrid chemical/lithographic process. In this process, the core portion of the component wafer may be doped by masking off the cladding portion and exposing the core portion at high temperatures to a germanium-based or fluorine-based chemical dopant. The lithographic mask is analogous to photoresist in

that it prevents the underlying cladding material from being doped along with the core material. The mask is then removed, and a process is repeated for the cladding portion.

In another preferred embodiment, the component wafer may be formed by a flame hydrolysis process similar to processes used in planar waveguide technology. Examples of applicable flame hydrolysis processes are described in Kilian, A. *et. al.*, "Birefringence Free Planar Optical Waveguide Made by Flame Hydrolysis Deposition (FHD) Through Tailoring of the Overcladding," Journal of Lightwave Technology, Vol. 18, No. 2 (February 2000), pp. 193-198, and Suzuki, S., *et. al.*, "Integrated-Optic Ring Resonators with Two Stacked Layers of Silica Waveguide on Si," IEEE Photonics Technology Letters, Vol. 4, No. 11 (November 1992), pp. 1256-1258, which are incorporated by reference herein. The desired refractive index profile may be achieved during the flame hydrolysis process. During this process, a soot having the appropriate core doping is formed on the entire wafer, the core portion is masked, and cladding portion is etched away. The wafer is sintered to convert the soot in the core to a doped silica glass. Another soot layer having appropriate cladding doping is deposited across the entire wafer. The wafer is again sintered, whereby the cladding region has a single silica glass layer and the core region has two silica glass layers. The wafer is then planarized using a chemical-mechanical process to remove the second silica glass layer from the first layer, the resulting wafer having the desired refractive index profile.

FIG. 7A illustrates steps for bonding the component wafers together into a bonded stack in accordance with the preferred embodiments, the steps being diagrammatically illustrated in FIG. 7B in a simplified two dimensional representation showing two voids only. At step 702, depending on which method was used to generate the component wafers, each component wafer lies on its own silicon substrate, or if no such substrate is present, one is attached. FIG. 7B shows two such assemblies, a first component wafer 752 lying on a substrate 750, and a second component wafer 756 lying on a substrate 754. A variable k used for describing the steps of FIG. 7A his initialized at step 704. At step 706, the second wafer is turned onto the first wafer and bonded, using a bonding process similar to any of a variety of $SiO2$-$SiO2$ bonding processes known in the art. Examples of applicable bonding processes are described in Cheng, Y. *et. al.*, "Localized Silicon Fusion and Eutectic Bonding for MEMS Fabrication and Packaging," IEEE Journal of

Microelectromechanical Systems, Vol. 9, No. 1 (March 2000), pp. 1-8, and Maszara, W. *et. al.*, "Bonding of Silicon Wafers for Silicon-on-Insulator," Journal of Applied Physics 64 (10) (15 November 1998), pp. 4943-4950, which are incorporated by reference herein. After this step, substrate 754 of the second wafer 756 lies on top of a two element bonded stack as shown in FIG. 7B.

At step 708, substrate 754 is removed using known methods, whereby an open two-element bonded stack comprising first wafer 752 and second wafer 756 remains on the first substrate 750. The process is repeated at steps 710-716, wherein a third wafer 760 lying on a third substrate 758 is turned on top of the two-element bonded stack to form a three-element bonded stack, with the substrate 758 lying on top. Substrate 758 is removed, whereby an open three-element bonded stack remains. The process continues for each component wafer until all have been added onto the bonded stack. The first substrate 750 may then be removed from the bottom end, where in the bonded stack is ready for drawing into the desired transformer element. After the bonded stack is formed and prior to attachment of the sacrificial preform sections, an annealing or laser ablation process may be applied to smooth out any rough edges or discontinuities in the void cavities.

To save time in the transformer element fabrication process, a massively parallel process may be applied, wherein the component wafers are not added one-by-one onto an existing bonded stack, but are rather bonded in separate but concurrent steps to adjacent component wafers to successively build larger and larger adjacent sections of bonded stack. For simplicity, an example in which exactly $2^N$ component wafers are bonded is presented here, the method being readily extensible to bonded stacks having different numbers of component wafers. Starting with a counter variable $m = 0$ and for each value ($m = 0, 1, 2, \ldots N-1$), $2^{N-m}$ groups of longitudinally adjacent stacks of $2^m$ wafers each are bonded together, two at a time, in separate but concurrent fashion. This results in $2^{N-m-1}$ groups of longitudinally adjacent stacks of $2^{m+1}$ wafers each. The process comtinues for each m until $m=N-1$, wherein the complete bonded stack is formed.

By using parallel construction of many adjacent portions of the bonded stack, time is saved as compared to incrementally building a common bonded stack one wafer at a time, assuming that the massively parallel resources are available. For example, for a bonded stack having 1024 wafers ($N=10$), and where $\Delta T$ represents a single bonding time,

the bonded stack may be built in a time of approximately 10ΔT, as opposed to a time of approximately 1024ΔT if the bonded stack is formed one wafer at a time.

FIG. 8 illustrates steps for fabricating a microstructured optical fiber transformer element in accordance with a preferred embodiment in which void patterns are not formed into the component wafers individually, but rather are formed into the bonded stack of component wafers. FIG. 8 shows a step 802 of generating component wafers having the desired refractive index profiles similar to the step 602 of FIG. 6, a step 808 for attaching a sacrificial preforms to each and of the bonded stack similar to step 608 of FIG. 6, a drawing step 810 similar to drawing step 610 of FIG. 6, and a clipping step 812 similar to drawing step 612 of FIG. 6. However, at step 804 the component wafers are bonded together into a bonded stack prior to the formation of voids. At step 806, the desired void pattern (and, inherently, the desired void pattern profile as distance z changes) is lithographically formed into the bonded stack as a whole.

FIG. 9A illustrates steps for forming void patterns into the bonded stack as a whole, the steps being diagrammatically illustrated in FIG. 9B in a simplified two dimensional representation showing two voids only. Generally, many iterations of lithographic masking and etching on the bonded stack are required to obtain the desired void pattern profile. At step 902, the bonded wafer stack 950 has been formed. A variable k used for describing the steps of FIG. 9A his initialized at step 904. At step 906, a photoresist mask 952 is applied to the bonded stack 950. At step 908, the bonded stack is etched and the mask layer removed. At steps 910-916 the etching process is repeated for the next mask 954. Importantly, although FIG. 9B shows one etch per component wafer, there may be several etches corresponding to a single component wafer, or alternatively, a single etch may encompass more than one component wafer. After the formation of voids is complete and prior to attachment of the sacrificial preform sections, an annealing or laser ablation process may be applied to smooth out any rough edges or discontinuities in the void cavities.

Whereas many alterations and modifications of the present disclosure will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that the particular embodiments shown and described by way of illustration are in no way intended to be considered limiting. For example, the

above-described method for fabricating a microstructured optical fiber transformer element may be readily extended to build optical fibers or optical fiber devices having arbitrarily complex cross-sectional void patterns, material patterns, and/or refractive index profiles. Moreover, the optical fiber or optical fiber device may have many different sections in the axial direction having drastically different void patterns, material patterns, and/or refractive index profiles. As an additional example, axially periodic structures may be formed at intervals of $(n + m/4)\lambda$ to form devices such as Bragg gratings or other interferometric devices. Therefore, reference to the details of the preferred embodiments are not intended to limit their scope, which is limited only by the scope of the claims set forth below.